

Special Report 32

LITERATURE SURVEY OF MOISTURE MIGRATION IN SOILS
DUE TO THERMAL GRADIENTS

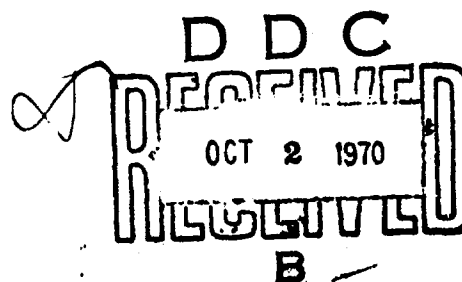
by

J. O. Osterberg and W. N. Fead



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PREFACE

This literature survey was conducted under Contract DA-11-190-ENG-6 with Northwestern University. The purpose of this study was to discover what work had been done on vapor diffusion in soils, in order to uncover any theory which might explain the occurrence of ice lenses in permafrost.

The work was done by Dr. Osterberg and Mr. Fead, Department of Civil Engineering, Northwestern University. The investigation was under the supervision of Mr. W. K. Boyd, then Acting Chief, Frozen Ground Basic Research Branch.

INTRODUCTION

The occurrence of ice lenses in coarse sands and gravels in the permafrost region cannot be explained by the accepted theories of frost action of soils. Laboratory experiments and field observation in non-permafrost regions show that sands and gravels freeze homogeneously and no ice segregation occurs. An explanation that has been proposed is that water evaporates from below in the gravel pores and condenses on the cooler surfaces nearer the ground surface. If enough water can condense and freeze at a given level to form a layer thick enough to withstand the next season's thaw, it can grow bigger each winter, and hence form the thick ice layers observed.

The literature was searched to find if any work had been done on the problem of ice lenses in permafrost, to find what work had been done on vapor diffusion in soils due to a thermal gradient, and to uncover any theory which might explain the occurrence of ice lenses in gravel in permafrost regions. The only literature uncovered relating to the subject concerned vapor migration in soils when subjected to thermal gradients at temperatures above freezing. There is considerable disagreement and confusion regarding the method and amounts of vapor diffusion. From the literature studied, the following remarks can be made.

1. Since surface tension increases and viscosity decreases with decreased temperature, water in vapor form tends to migrate to the cooler side of a soil system, because capillary pressures are greater and the vapor pressures therefore lower, and water in liquid form tends to migrate around the soil particles to the cooler side. Most experiments measure both of these combined and it is found that measurable amounts of water can be transported by thermal gradients, but results differ widely on the quantity.

2. In those experiments where quantities are measured, it is found to vary widely with soil type and with water contents.

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3. When the wet and dry portions of the soil columns were separated by an air space, thus allowing thermal migration only in the vapor phase, the quantity was greatly decreased. Several investigators report that the quantity transported by vapor diffusion is very small.

4. Rengmark and Erikson (ref. 5) show that much more water is transported from the warm side to the cold side when the voids are large, and attribute this to convection currents in the voids. In fact the authors say that only through convection can large quantities of water vapor be transported.

5. No experiments or theories were uncovered which could explain the formation of ice lenses in gravel in permafrost.

6. Several references describing experiments in fine-grained soils were found. The quantities of water transported were reported to be small.

7. It is possible that, in the large voids of gravel, considerable moisture can be transported by convection of vapor and deposited and frozen on the cold surface. A cycle could occur in which a continuous supply of water is brought to the freezing ice lens by the vapor transported mainly by convection currents. Since apparently no experiments have been made on this problem, it is suggested that some simple preliminary experiments be attempted.

1. Lebedev, A. F., THE MOVEMENT OF GROUND AND SOIL WATERS. Proceedings, First International Congress of Soil Science, vol. I, p. 459, 1927 (Translated by J. S. Joffe).

Measurements of relative humidity were made in various soils at various depths. Relative humidity is 100% for all soils when their water contents are in excess of their hygroscopicity. For water content smaller than the hygroscopicity, the humidity decreases as water content decreases, and decreases with an increase in temperature at a constant water content. In natural soils, the relative humidity is always 100% below a depth of 5 to 10 cm. Therefore the vapor pressure down in the soil is a function of temperature. At night the relative humidity is often less in the upper 1 cm of soil than in the atmosphere, and therefore vapor moves into the soil. Measurements were presented to prove this. In Odessa as much as 72 cm of water per year can move into the top layer of soil from the air.

There can also be upward movement of moisture during the frequent dry periods of spring and summer when the water content of the upper layer drops below its hygroscopicity and therefore the vapor pressure is less than below.

Temperature plays an important role, as shown by temperature variations over several days at different depths. When the atmosphere cools, the temperature gradient in the soil is such that the vapor pressure is greater at 10 cm depth than at 5 and 20 cm, and thus there is a loss from this depth both downward and upward. Usually in early morning and early evening, the vapor pressure in the upper 5 cm is greater, and the vapor condenses lower down. As a consequence, the upper crust is wetter and the soil below this crust is drier during summer cold periods than during warm periods.

Lebedev measured an increase of 66 mm of water per cm^2 in the upper crust during one season, and concluded that this was transported upward to the soil surface in the vapor phase.

2. Bouyoucos, G. J., EFFECT OF TEMPERATURE ON THE MOVEMENT OF WATER VAPOR AND CAPILLARY MOISTURE IN SOILS. Michigan State Agricultural College, Experiment Station Bulletin No. 22, 63 pages, 1915.

From Bouyoucos's summary:

"(1) When one half of a column of soil of uniform moisture content is maintained at 20 and 40C and the other half at 0C for eight hours, the percentage of water moved from the warm to the cold soil increases in all the different types of soil with rise in moisture content until a certain water content is reached and then it decreases with further increase in moisture content. The results then plot into a parabola. The per cent of moisture at which the maximum thermal translocation of water occurs is different for the various classes of soil, but the percentage of the maximum thermal translocation of water is about the same for all classes of soil for any one of the temperature amplitudes. The percentage of moisture at which this maximum thermal translocation occurs is designated as THERMAL CRITICAL MOISTURE CONTENT.

"These results are contrary to what might be expected from the laws of surface tension and viscosity. They have led to the conclusion that the capillary movement of water in moist soils is not controlled entirely by the

curvature of the capillary films, as is generally believed, but also by the unsatisfied attractive forces of the soil for water.

"(2) When a moist column of soil is kept at 20 to 40C and a dry column of soil at 0C for eight hours, and the two columns are separated by an air space, the percentage of moisture distilled over from the moist and warm column to the dry and cold column of soil is very insignificant for both amplitudes of temperature, and about the same for all moisture contents.

"These results lead to the conclusion (a) that the amount of water lost from the soil by water vapor is very small, (b) that there is no rising of vapor during the night from the warmer soil below to the cold soil above, and (c) that the source of water of the dew is not derived from the soil vapor, as is commonly believed.

"(3) When a moist column of soil is in contact with a dry column of soil and the former is kept at 20 and 40C and the latter at 0C for eight hours, the amount of moisture moved from the moist and warm soil to the dry and cold soil increases with temperature and with moisture content. But when the moist column of soil is maintained at 0C and the dry column of soil at 20 and 40C for the same number of hours, there is very little, if any, movement of water from the former to the latter.

"These results have led to the conclusion that temperature has a very marked influence on the conservation of moisture by moilches.

"(4) No thermo-osmotic phenomena were observed in soils.

"(5) The research on the effect of temperature on the rate of percolation of water in soils shows that in the case of sandy loam, silt loam, clay loam, clay and muck the rate of flow increases with the rise in temperature up to about 30C and then decreases with further rise in temperature. In the case of sand, however, the rate of flow increases with a constant rising of temperature. In the former soils the results are explained under the hypothesis that the colloidal material present swells with increase in temperature and tends to close the channels through which the water flowed.

"(6) The water-holding capacity of soils decreased with rise in temperature, but this decrease is not due entirely to the diminished surface tension of the soil water but also to other factors.

"(7) The rate of flow of air through soils decreases with rise in temperature. This diminution is not entirely due to the increased viscosity of the gases, but in addition to some changes which the temperature produces in the soil.

"(8) Temperature has a tremendous influence upon the aeration of soils. This influence is not due merely to the expansion of gases of the soil, as is commonly believed, but also the absorption of gases by the soil at different temperatures, and to the aqueous vapor."

3. Jones, H. E. and Kohnke, Helmut, THE INFLUENCE OF SOIL MOISTURE TENSION ON VAPOR MOVEMENT OF SOIL WATER. Proceedings, Soil Science Society of America, vol. 16, no. 3, 1952.

Soils were placed in tubes and subjected to thermal gradients similar to Bouyoucos's test. Water vapor movements were measured and

expressed as a function of the pF value for a given soil. The pF value is the logarithm of the soil tension in centimeters of water. Thus a capillary tension of 1000 cm would be a pF of 3.

All studies were conducted in the laboratory. Vapor movement was effected by vapor pressure differences obtained by creating a sharp temperature interface at the midpoint of horizontal soil columns. The influences of such factors as soil porosity, initial moisture content, and vapor pressure gradients were determined.

The movement of water vapor in the two soils and four soil separates studied increased rapidly with moisture tension up to a certain level, then decreased sharply.

The pF at which vapor movement was initiated and at which maximum movement occurred increased with a decrease in particle size.

The volume of unsaturated soil pores, not their size, seems to govern the soil moisture content at which vapor movement begins.

The volume of vapor movement in disturbed soil samples under a given vapor pressure gradient is regulated by the balance of unsaturated pore space, evaporating surfaces, and moisture reserve existing in the soil.

Maximum vapor movement occurred at moisture tensions slightly below the wilting point, suggesting a mechanism by which plants may resist drought injury.

Temperature-induced vapor pressure gradients seem to be mainly responsible for water vapor transfer in soils.

4. Rollins, R. L., Spangler, M. C., and Kirkham, D., MOVEMENT OF MOISTURE UNDER A THERMAL GRADIENT. Proceedings, Highway Research Board, p.492-508, 1954.

The paper presents a theoretical equation, assuming a molecular diffusion process, for estimating the amount of water vapor moving through a soil. It also describes an apparatus and tests for measuring the quantities of water moving in the vapor phase. An excellent review of the literature is presented.

A plexiglass tube 10 cm long with 4 cm inside diameter is filled with a soil which has been weighed and carefully mixed with a predetermined weight of water. Porous ceramic disks are placed on the ends and are sealed in the apparatus to make a closed system. Two outlets are provided at each end. One outlet is connected to a mercury manometer and the other outlet is attached to a long capillary tube to ded several times, which connected the two ends. A small drop of mercury in the capillary tube measured the rate of flow from one end to the other.

Two soils were used; a silt loess at 20% and a fine sand at 5% water content. At one end of the soil tube, temperatures were maintained at 40, 30, 20 and 10C in different experiments; at the other end, the temperature was kept constant at 1C. In one series of tests the two ends were connected by the capillary tube so that flow could be measured in a circulating system and in the other series no circulation between ends was allowed.

It was concluded that the flow is greatly influenced by the density and percent of air-filled voids. By comparing non-circulating and circulating systems it was concluded that the predominant method of movement of liquid is in the vapor state. The measured values of flow were approximately six times that computed from the theory derived using several assumed soil constants.

5. Rengmark, F. and Eriksson, R., AN INVESTIGATION OF VAPOR TRANSPORTATION IN SOIL, Proceedings, Third International Conference on Soil Mechanics and Foundation Engineering, vol. I, p. 184-185, 1953.

To study the possibility of moisture transfer to the underside of an asphalt pavement by vapor transfer across an underlying sand or gravel layer, the authors made experiments with glass tubes 30 cm long and 5 cm in diameter filled with different materials. A 5-cm layer of air-dried fine sand (0.074 - 0.125 mm) was placed at the tops of all tubes. A water level was maintained at 20 cm below the bottom of the tubes and the space between the water and the top layer was filled with gravel, or sand of different sizes, or left empty. One set of tubes was maintained at room temperature for 30 days. The other was kept in a refrigerator with the top at +4C and the water at +20C for 30 days. In the tests with a temperature gradient, the moisture content of the upper layer increased 30.9% in the tube with air as the intermediate layer and 3.5% in the tube with gravel as the intermediate layer. For sand, the increase in moisture content decreased as the size decreased, and was as small as 0.7% for the 0.125 - 0.25 mm size. For no temperature gradient, the water content increased 16.2% with air as the intermediate layer, and 0.2% for the gravel and sands.

The experiments show that vapor diffusion is small in fine grained soils and that the transfer of moisture by convection can be large when the air voids are large. In fact the experiments indicate that transfer of water by any means other than convection currents is negligible. Even with no temperature gradient, considerable moisture is transmitted through air by convection.

6. Beskow, Gunnar, TJÄLBILDINGEN OCH TJÄLLYFTNINGEN (SOIL FREEZING AND FROST HEAVING), Sveriges geologiska undersökning, Årsbok 26, Ser. C, no. 375, 1935 (Translated by J. O. Osterberg, published by Northwestern University, Evanston, Illinois, 1947).

Only reference to moisture migration is on pp. 89 and 90 (of translation). Beskow considers flow by diffusion across a crack or fissure in a soil. He assumes a temperature drop across a fissure of 1-2C/cm. Then, using the vapor pressure of water at close to 0C, and a coefficient of diffusivity of 0.20, he computes the amount of water that can be transferred. He concludes that the diffusion due to temperature difference across a crack is small and can amount to only a few millimeters per day.

This computation is only for a crack. In a gravel deposit in permanent frost, the temperature gradient could conceivably be higher. But most important is the fact that Beskow does not consider moisture transfer by convection currents. If convection currents can increase the moisture transfer by, say 10 times (see reference 5), then the amount of moisture transferred by diffusion could easily form a thick ice layer in the upper part of the gravel.

7. Buckingham, Edgar, STUDIES ON THE MOVEMENT OF SOIL MOISTURE, U. S. Department of Agriculture, Bureau of Soils, Bulletin No. 38, Feb. 14, 1907.

A surface of water or moist soil was exposed to evaporation into a confined space which was in communication with the outside air through a column of soil of known height and cross section. Whatever water escaped from below the column of dry soil had thus to escape by pure diffusion, because there was no capillary connection between the column of soil and the water or moist soil from which the loss was being measured.

In the first experiment, the soil from which the evaporation was to take place was spread in a loose layer about half an inch thick in the bottom of a glass tumbler, while the upper 2 in. of the tumbler were filled with coarse dry sand and supported on wire gauze and cheese cloth. This left about $\frac{1}{2}$ in. of air space between the damp soil in the bottom and the dry sand above it.

Ten tumblers were used: 3 tumblers with soil, solid manure, and water contents 17, 20, 27%; 3 tumblers with soil, liquid manure, and moisture contents 10, 16, 22%; 3 tumblers with soil, tap water, moisture contents 12, 17, 23%; 1 tumbler with water. The soil was a sandy loam from Takoma Park, Maryland.

Summary of results:

(1) There were no systematic differences in the losses related to the differing water content of the solids.

(2) The soils treated with solid manure lost water slightly faster than the others, but only to an extent which might be accounted for by assuming that the heating effect of the rotting manure kept their temperature about 1°C higher than the others, thus increasing the vapor pressure of the water over them.

(3) With this exception the loss of water was the same, within the experimental errors, for all the tumblers, including the one in which the evaporation was from a free water surface instead of from water distributed in thin films over the surfaces of the soil grains.

(4) Comparison of the rates of loss, with and without the fan and turntable in motion, showed that the rate of loss was about three times greater into a 3-mph breeze than into the still air of the room.

(5) The rate of loss observed was approximately the same as might have been computed from known data and known principles with the aid of very probable assumptions. The known data referred to are the thickness, cross section, and porosity of the layers of dry sand; the temperature of the experiment and the humidity of the outside air (both known only approximately); and the free diffusion constant of air and water vapor. The known principles are the laws of the free diffusion of gases, and the fact, established by the writer's experiments (Bull. No. 25, Bureau of Soils, USDA), that the rate of interdiffusion of air and carbonic acid through four soils of varying types and conditions was approximately proportional to the square of the porosity of the soil (porosity here used as fraction of total volume not occupied by water or soil). The assumptions are that this rule holds also for the interdiffusion of water vapor and air; that the free space below the sand was sensibly saturated with water vapor; and that the 3-mph breeze was sufficient to prevent any sensible increase in humidity in the air immediately over the tumblers.

Conclusions:

(1) The free-air space below the sand was equally moist in all cases, probably very nearly saturated. In other words, the varying treatment of the soil as regards both manuring and moisture content did not influence the partial pressure of the water vapor in the air space above it.

(2) Hence, since resistance to escape by diffusion was as great as that offered by a 2-in. layer of very coarse, dry sand, no differences were perceptible, if any existed at all, between the case of evaporation from the damp soils treated in various ways and from a free water surface.

(3) As was to be expected, the diffusion of water vapor into the air through soils followed the same laws as the diffusion of air and carbonic acid under similar circumstances.

(4) The actual mean rate of loss of water was equivalent to about 1.4 in. of rainfall per year into still air, and about 4.3 in. into a breeze of 3 mph with the temperature about 20C to 22C, and the dewpoint about at the freezing point.

A second series of tests used a soil column of varying porosities instead of the sand covers. The results indicated that the diffusion varied with the 2.2 power of the porosity. Curves of final water content distribution bear a marked resemblance to drainage curves, etc. of soils. These tests showed that only about $\frac{1}{5}$ in. of rainfall per year would be lost on the basis of 17-day tests.

A third set of tests was similar to the second set except that the tops of the soil columns were open to the air instead of being closed. Comparable results are presented. From the author's conclusions:

"The first of the experiments showed that the open space below the sand was nearly saturated with water vapor and that it made no material difference whether this space was fed with water vapor from a free water surface or from damp soil. Hence we may assume that in the other experiments also the vapor space below the soil column was sensibly saturated. It could therefore not have had any more water vapor in it if it has been fed by evaporation from moist soil, no matter what the depth of the moist soil might have been below the level in question and consequently there could in no case have been a greater tendency for the escape of water vapor from this depth. The figures given for the rates of loss of water from the cups represent, consequently, the maximum amounts of loss by direct evaporation which could have occurred from moist soils of any thickness below the depths named and under the given conditions of temperature and humidity.

"The first, third and fourth experiments are virtually experiments on the effectiveness of mulches of various dry soils of varying depths and compactness, the mulch being made perfect and the conditions simplified by the entire elimination of capillary motion into the mulch from below. The loss from below the coarse sand, at the rate of 4.3 inches per year through 2 inches depth, shows that the protecting action of this mulch was by no means perfect, and with a more loose, open mulch the protecting action, supposing always that the capillary flow into and up through the mulch is negligible, would be still less perfect.

With the finer-grained soils of the fourth experiment the direct evaporation loss was less. But since the capillary action in these soils would, if they were in actual contact with the moist soil below, be considerable, we cannot conclude that these mulches would necessarily be more effective than in the coarse sand.

"The second experiment, while the most complicated, corresponds most nearly to practical conditions, and here we see that the direct evaporation loss from below a 12-inch layer of damp soil is quite insignificant, amounting at most to only 1 inch of rainfall in six years."

The paper contains 43 pages of experimental results and theoretical discussions of capillary action.

8. Puri, A. N., Crowther, E. M., and Keen, B. A., THE RELATION BETWEEN VAPOR PRESSURE AND WATER CONTENT SOILS, Journal of Agricultural Science, vol. 15, pp. 68-88, 1925.

Concludes that water adsorption at constant relative humidities is almost independent of temperature over the range from 20°C to 40°C if humidities are high, but decreases markedly with increasing temperature if relative humidities are low.

9. Cotnoir, L. J., WATER VAPOR AS A SOURCE OF SOIL MOISTURE, Proceedings, Soil Science Society of America, vol. 12, p. 88, 1947.

One paragraph, Estimate about 1.5 to 3 in./yr soil moisture from water vapor in atmosphere.

10. Croney, D., Lewis, W. A., and Coleman, J. D., THE CAUSES AND CONTROL OF SUBGRADE MOISTURE CHANGES, Proceedings, Second International Conference on Soil Mechanics, (Rotterdam), vol. 4, p. 211-218, 1948.

Gives curves showing some results of vapor movement research. States "the research showed that in cohesive soils moisture movements resulting from temperature gradients were negligible when the moisture content was above the plastic limit."

11. Brawand, Hans, ADSORPTION AND CONDENSATION OF ATMOSPHERIC WATER VAPOR INTO THE SOIL, Ph.D. Dissertation, Purdue University, 1951.

Discusses the adsorption of water vapor from the atmosphere and the increase in moisture due to the condensation of water vapor from the atmosphere.

Gives some interesting observed data concerning fluctuations of temperature and computed data concerning fluctuations of vapor pressure at various soil depths.